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SPATIAL AND TEMPORAL VARIABILITY OF NORTHWEST PACIFIC TROPICAL CYCLONE ACTIVITY IN A GLOBAL WARMING SCENARIO

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Abstract: Utilizing the Joint Typhoon Warning Center (JTWC) and Tokyo-Typhoon Center of the Japan Meteorological Agency (JMA RSMC TOKYO) best-track tropical cyclone (TC) data for the period 1951–2014, variations in spatial and temporal characteristics of Northwest Pacific TC activity for a global warming scenario are discussed. The results suggest that since the early 1960s, there has been an overall decreasing trend in the frequency of occurrence, intensity, peak intensity, length of movement, and lifetime of TCs. However, global warming has led to a linearly increasing trend in TC activity in eastern Asia, which indicates that Northwest Pacific TC activity decreases, but the frequency of landfalls and intensity are likely strengthened. Therefore, the threat of TCs towards eastern Asia is enhanced. The increase in TC activity in eastern Asia is likely the result of a strengthened Walker circulation due to an increasing temperature gradient between the northwest Pacific Ocean and the central and eastern Pacific Ocean. The strengthening Walker circulation could increase the magnitude of the vertical wind shear, relative vorticity, and meridional wind shear of low-level easterlies near the equator in the tropical Northwest Pacific, which affects the spatial and temporal variations of TC activity in the Northwest Pacific.

Key words: global warming; western North Pacific; tropical cyclone; spatial and temporal variability
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1 INTRODUCTION

In the past few decades, the ability to determine the cause of the formation, development, and influence of tropical cyclones (TCs) has been a significant challenge for the meteorological community. Simultaneously, the response of TC activity to global warming remains controversial, in part because of uncertainties in the historical TC records (e.g., Chan[1]; Landsea et al.[2]; Landsea[3]; Kossin et al.[4]; Vecchi and Knutson[5]; Emanuel[6]). During the last two decades, several studies have been devoted to answer this interesting but elusive question. Global warming has a pervasive influence on ocean sea-surface temperature (SST) and heat content, atmospheric temperature, water vapor, and atmospheric and oceanic general circulation patterns, all of which have a complex effect on TCs, which are not yet fully understood. Chan and Liu[7] demonstrated that in the NWP basin, there was no significant relation between typhoon activity parameters (i.e., annual frequency of typhoons, ratio of intense storms to the total number of tropical cyclones, and destruction potential) and the local SST warming during the period 1960–2003. Aspects of the association between global warming and tropical cyclones are uncertain in part because climate change is irregular but continuous. Our basic conceptual understanding of cyclones suggests that there could be a relation between cyclonic activity and SST. An SST of 26℃ is required for TC formation in the current climate. As the SST becomes warmer, certain tropical ocean basins may face an increasing number of more intense tropical cyclones (Gray et al.[8]). Elsner and Kocher[9] determined that SST has increased in the tropics by approximately 0.5℃ between 1970 and 2004. Anthes et al.[10] proposed that we should expect that a warmer and more moist environment would enhance overall cyclonic activity. Tropical cyclones form only over warm oceans, from which they gain

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energy. Emanuel et al.[11] applied this approach to quantify the possible influence of global warming on TC activity, suggesting that global warming should reduce the global frequency of hurricanes, though their intensity may increase in some locations. Knutson et al.[12] and Knutson and Tuleya[13, 14] conducted hurricane model simulations with large-scale thermodynamic conditions (atmospheric temperature and moisture profiles, and SST) derived from global warming experiments, and found that hurricanes simulated under warmer conditions are stronger and have higher precipitation rates than under present-day conditions. Tropical SSTs have trended upward over the past 50 years (Kumar et al.[15]). The warming trend in the oceans is generally believed to be associated with ongoing global warming since the 1970s (Houghton et al.[16]). In the Western North Pacific (WNP) basin, upward trends were found over the past three decades proportionally with the number of intense typhoons with a maximum wind speed greater than 59 m/s (Webster et al.[17]). According to Trenberth[18], there is growing evidence that global warming enhances a cyclone's damaging winds and flooding rains. Elsner et al.[19] found that the strongest tropical storms are growing in strength, with the most notable increases in the north Atlantic and northern Indian Oceans. Emanuel[20] demonstrated that the annual accumulated PDI has increased markedly in the northwest Pacific and north Atlantic basins since the mid-1970s and attributed the upward trend to both longer storm lifetimes and greater storm intensities. Kossin et al.[4] constructed a new 23-year global record of TC intensity and found similar trends in the PDI along with the intensity of hurricanes in the Atlantic basin. In a study by Wu et al.[21], the annual accumulated PDI significantly trended upward only in the north Atlantic basin compared to the SST warming in the north Atlantic, north-west Pacific, and eastern-north Pacific basins over the past 30 years. According to Saunders and Lea[22], a 0.5℃ increase in SST is associated with a 40% increase in hurricane frequency and activity in the north Atlantic.

Based on the recommendations of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2013), although the long-term scale (century) changes, the predicted enhancement in TC activity has low reliability, but since 1970, the enhancement in Atlantic tropical cyclone activity is almost certain[23]. However, it is not clear how the TC activity changes in the Northwest Pacific. Applying a global warming scenario, this study focuses on the temporal variation of TC activity (occurrence frequency, intensity, peak intensity, length of movement, lifetime, and spatial variation of TC activity) during different stages of a TC's life cycle to explore the variability and possible mechanisms of Northwest Pacific TC activity due to changes from global warming.

2 DATA

We utilized the Joint Typhoon Warning Center (JTWC) and Tokyo-Typhoon Center of Japan Meteorological Agency (JMA RSMC TOKYO) TC best-track data covering the period of 1951-2014 in the WNP basin. The data sets commonly include the locations of the TC centers and maximum sustained wind speeds at 6 h intervals.

SST is obtained from the University of Maryland (UMD) and Texas A&M University (TAMU) reanalysis products SODA_2.2.4. The vertical resolution is spaced unequally with a total of 40 levels. The SODA_2.2.4 SST data, covering the period 1945-2010, has 0.5°×0.5° horizontal resolution and a depth of 100 m. Levels 1–9 (0–96.92 m) are selected in the study to calculate the Pacific surface temperature.

Wind field data is from Reanalysis 2 of the general circulation model from the National Center for Environmental Prediction and the Department of Energy (NCEP/DOE). The horizontal/vertical winds and geopotential height are separated into 37 pressure levels and a horizontal resolution of 2.5°× 2.5° for the period 1951–2014.

3 RESULTS

3.1 *Statistical characteristics of northwest Pacific TC activity*

Over the period of 1951–2014, TCs occurred over the Northwest Pacific including the South China Sea, among which there were 1879 TCs over the Northwest Pacific including 430 super typhoons (maximum wind speed is greater than 57.79 m/s), and 241 TCs over the South China Sea including 6 super typhoons. Significant inter-annual and inter-decadal variability are exhibited in the long-term trends in occurrence frequency, super typhoon frequency, intensity (average wind speed), peak intensity (peak wind speed), length of movement, and lifetime.

Figure 1a indicates that between the early 1950s and late 1950s, the frequency of occurrence rapidly increased, whereas between the early 1960s and 2014, the frequency of occurrence decreased; the frequency of occurrence of Northwest Pacific super typhoons between the early 1950s and late 1970s decreased, but it increased between the late 1970s and 2014. Fig. 1b illustrates that between 1951 and 2014, the Northwest Pacific TC intensity and peak intensity dramatically decreased. Fig. 1c and d indicates that there are no significant long-term changes in the length of movement and lifetime of TCs, although they do slightly decrease. From the early 1960s, the frequency of occurrence, intensity, peak intensity, length of movement, and lifetime of TCs showed a decreasing trend. While it is certain that the Northwest Pacific TC activity was reduced after the early 1960s, the trends after the mid-1970s are more reliable because America used observation satellites beginning in 1974, which increased the accuracy of the data.

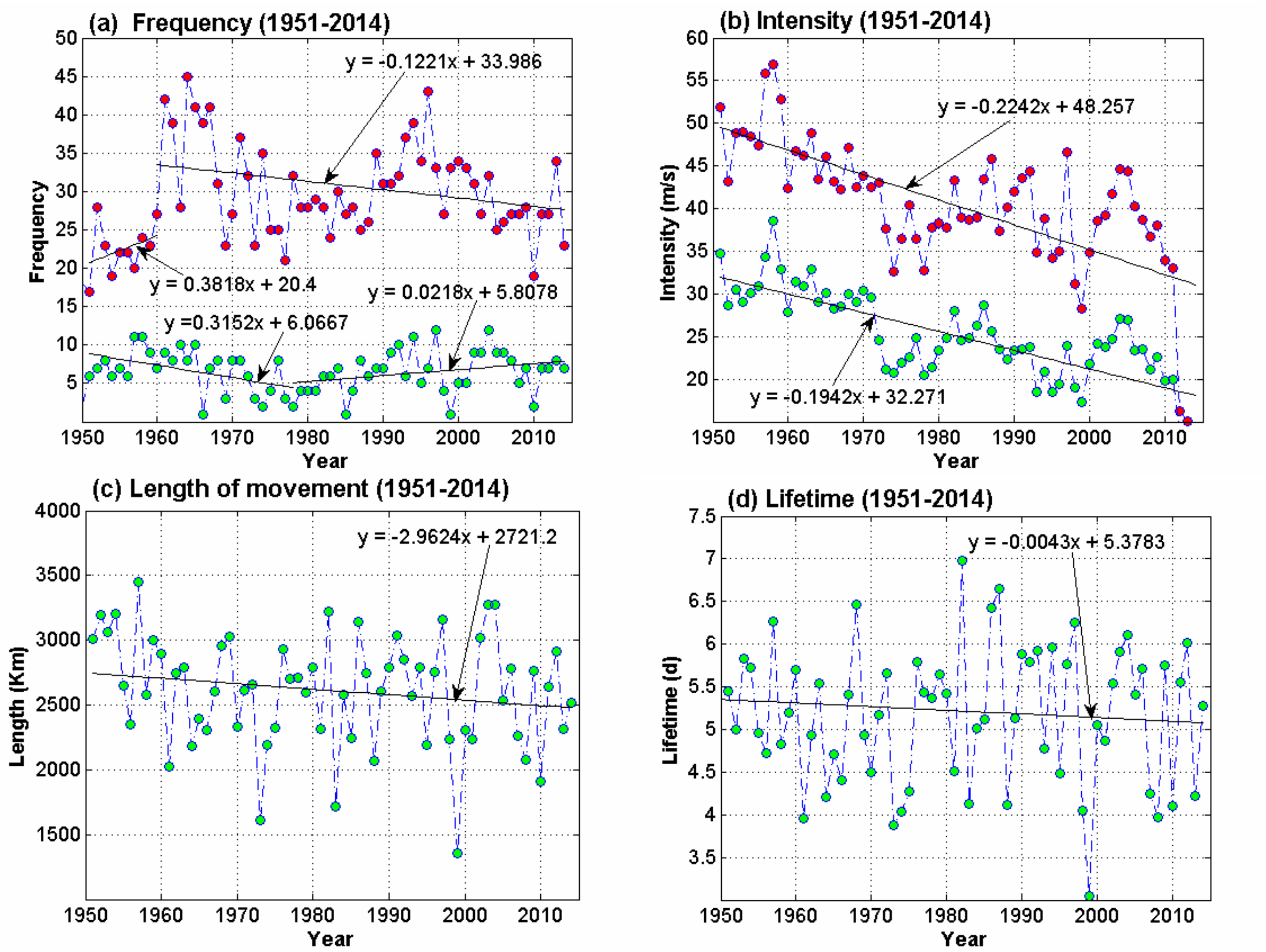

Figure 1. Time series of annual data over the period 1951–2014 based on the JTWC dataset for (a) TC frequency (the red dot shows the TC frequency, the blue dot shows super typhoon frequency), (b) intensity (the red dot shows the intensity, the blue dot shows the peak intensity) (m/s). Based on the JMA dataset, (c) length of movement (km), (d) lifetime. Straight lines indicate the trends and the inspection through 95% confidence level.

Utilizing the JMA RSMC TOKYO and Shanghai Typhoon Institution of China Meteorological Administration (CMA-STI) best-track data sets, Wu and Zhao[24] concluded that the intensity and peak intensity started to decrease from the mid-1970s, which is consistent with the results presented here. Additionally, they concluded that the frequency of super typhoon occurrence significantly decreased from the late 1950s to 2005, which is in disagreement with the results presented here; this might be due to the different data sets and different analysis methods.

3.2 *Spatial and temporal variability of northwest Pacific TC activity*

3.2.1 SPATIAL AND TEMPORAL VARIABILITY AT DIFFERENT STAGES DURING THE LIFE CYCLE

Presently, most studies focus on the spatial and temporal variability of the source location of TC formation and the factors that are influenced by the TC. TC activity has not been studied over a complete life cycle; the spatial and temporal variability of TC activity intensity on the whole cannot be evaluated. The TC life cycle can be divided into four different stages: 1) genesis: TC genesis is defined as occurring when a TC reaches wind speeds of at least 17 m/s, 2) development: the development stage is a time when the central pressure decreases continuously, including a temporary period when the central pressure does not change, 3) maturity: the mature stage is defined as the period from the end of the development stage to the beginning of the decay stage, and 4) decay: the decay stage is a period during which the central pressure rises monotonically (Wada A and Usui N[25]). Here, each TC central position over the Northwest Pacific ocean is counted in 5°× 5° bins to calculate the ratio of the numbers of TCs in each stage of their life cycle.

Figure 2 illustrates the horizontal distribution of TC locations for each stage of the life cycle. TCs are frequently formed around 127.5°E to 145°E, 7.5°N to 145°N in the Northwest Pacific, and around 115°E, 15°N to 20°N in the South China Sea (Fig. 2a). Previous studies indicate a different TC genesis location; for example, Zhou et al.[26] concluded that TCs are frequently formed around 130°E, 12.5°N. The differences might be due to the different time scale and data sets. Long-term changes show a trend in the TC forming source location: a notable increase over the northeastern Philippine Sea, decrease over the southeastern Philippine Sea (blue shading), and no significant changes over the South China Sea. Note that an increase in the frequency of occurrence in a specific region could reduce the average TC intensity over the local and surrounding regions because newly generated TCs usually have the weakest intensity, less than 17 m/s. This implies that the TC forming source location moves northeast, which lessens the threat to the Philippines.

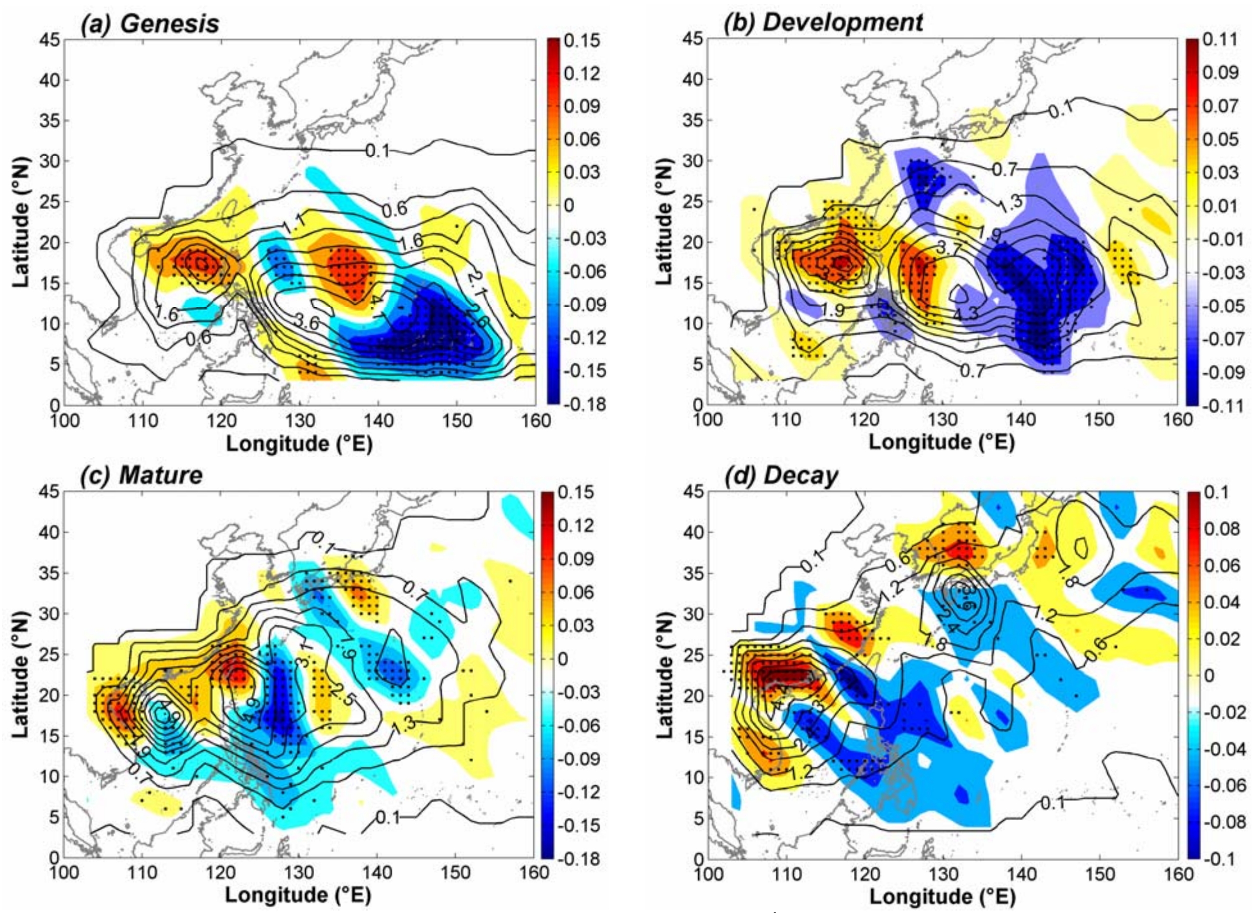

Figure 2. Climatology (black contour %) and linear trends (shading % decade^{-1}) over the period 1951–2014 based on the JTWC dataset for the (a) formation, (b) development, (c) maturity, and (d) decay stages. Black dots are marked for grid points where the linear trends are statistically significant at the 90% confidence level.

Figure 2b illustrates that the stages of TC development are mainly located over the eastern Philippine Sea. There is a notable increasing trend over the west and the north (red shading), and a significant decreasing trend over the east and the north (blue shading). By contrast, the stages of TC development show no change in their spatial distribution over the South China Sea, which implies that TCs move slowly over the South China Sea.

Figure 2c depicts the TC in the mature stage, which shows the climatology of the location of maximum intensity (contours) and its long term change (shading). The mature stages are mainly located over the western Philippine Sea (122°E, 22°N) and South China Sea (112°E, 17.5°N). The long-term change shows an increasing trend (red and yellow shading), which appears as a belt that mainly extends toward the west and north along the coastline south of 30°N. There are two areas with significant linear changes: Taiwan Island and the coastline of the northeastern Indo–China Peninsula. The mature location is shown to approach China’s coastline, which enhances China’s risk of being impacted by typhoons. TC intensity starts to decrease in the southern and northeastern locations of the belt. These features confirm that the expected changes based on the changes have indeed been occurring over the WNP basin. Except north of 30°N, the TC intensity begins to decrease in regions southeast of the Philippines (blue shading).

Figure 2d illustrates that the TC decay stages are mainly located in the southeastern and southern coast of China, the Indo–China Peninsula, and Hainan province. This also indicates that the TC landfall locations are mainly located along the southeastern coastline of China, the Vietnamese coastline, the coast from Fujian province to Leizhou Peninsula, and the southern coast of China. Most southern parts of China are affected. Another region located in the middle (134°E, 32°N) is formed in Kyushu, Japan. Over the Sea of Japan (134°E, 37°N), north of the middle area, the trend clearly increases.

3.2.2 SPATIAL AND TEMPORAL VARIABILITY OF TRACK FREQUENCY, OBSERVED INTENSITY, LENGTH OF MOVEMENT, AND LIFETIME

Spatial and temporal variability of the TC life stages may reflect the spatial variability of each stage of intensity during a complete TC life cycle and may also indicate which regions would be threatened by the different intensities. The contour and shading in Fig. 3a represent the spatial division and long-term change in track frequency. The TC track frequency is defined as the number of TCs passing through each 5°×5°grid box, which may indicate the threat of a TC in a certain region. The climatology of the track frequency can explain two high cores in climatology of the location of maximum intensity near Hainan Island and Taiwan (contour of Fig. 2a). It is easy to suppose that TCs have a greater chance of attaining their maximum intensity in a grid if a greater number of TCs pass through the same grid. Actually, the two high centers of the location of maximum intensity lie along two main passing routes of the TC, which are characterized by straight westward and curvy northward tracks from the eastern tropics of the WNP (black arrows in Fig. 3a). Similarly, the long-term change in the track frequency may also account for the shift of the location of maximum intensity towards the East Asian continent. Comparable spatial patterns are observed between the track density and the location of maximum intensity (contour of Fig. 2c); there are positive signs over all of Taiwan and the eastern coast of Japan, and the track frequency has two clear negative signs in the South China Sea and the tropical WNP more TCs move to Taiwan and Japan, which is related to the strengthening of the monsoon trough and the shift of the northwest Pacific sub-tropical high-pressure belt towards the northeast. The track frequency cannot completely explain the spatial patterns of maximum intensity (mature stage) since the two shadings do not completely overlap. Furthermore, the locations of the maximum track frequency entirely cover Taiwan, and the locations of the maximum intensity increase notably in the east and south of Taiwan. The increase in the track frequency near the coastline in eastern Vietnam is not clear (yellow shading), but in that region there is a hint that the maximum intensity (mature stage) forms regionally.

The observed TC intensity for each 5° × 5° bin of latitude–longitude grid is calculated by averaging the maximum wind speeds of those TCs that entered the box during the period 1951–2014 (Ho et al.[27]). The spatial pattern of the contour shown in Fig. 3b indicates that the location of the maximum observed intensity is in the east of Taiwan. Conversely, the intensity decreases in the southeast of Philippine (blue shading), increases in the northwest Pacific (red shading), north of 20°N, and west of 135°E. It is not a coincidence that spatial patterns in the observed intensity and linear trends in track frequency are similar in the tropical and mid-latitude zones. For example, the two main regions (Fig. 3a, blue shading) where track frequency decreases are flanking regions of the whole region where the intensity of observed TCs decreases. The TCs that affect Taiwan mainly come from the southeast. Its track density clearly increases, and its observed intensity also increases. Additionally, there are more TCs that pass through it.

Figure 3c indicates that TCs are mainly generated between 160°E and 175°E, 3° N and 15°N, and the southern Philippines (120–130° E, 5–10°N), which has a longer length of movement (contour). In the long term, the source location of TCs exhibits a notable increase between 160°E and 175°E, 3°N and 30°N, and near the east Asian continent (110–125°E, 5–33°N), and a notable decrease over the eastern Philippine Sea (blue shading). Figure 3d indicates that TCs are mainly generated between 160°E and 175°E, 3°N and 15°N and have longer lifetimes (contour). In the long term, the source location where TCs form exhibits a notable increase between 130°E and 170°E, 3°N and 30°N and the northeastern Philippines (125–130°E, 10–17°N) (red shading), and a notable decrease over the eastern Philippine Sea (130–150°E, 3–20°N) (blue shading).

The region where the linear change of different stages of the TC life cycle (i.e., genesis, development, maturity, and decay), frequency, track frequency, observed intensity, length of movement, and lifetime increases approaches the central Asian coastline. Northwest Pacific TC activity decreases, but because of the spatial distribution of the linear changes, the threat of TCs toward eastern Asia is enhanced.

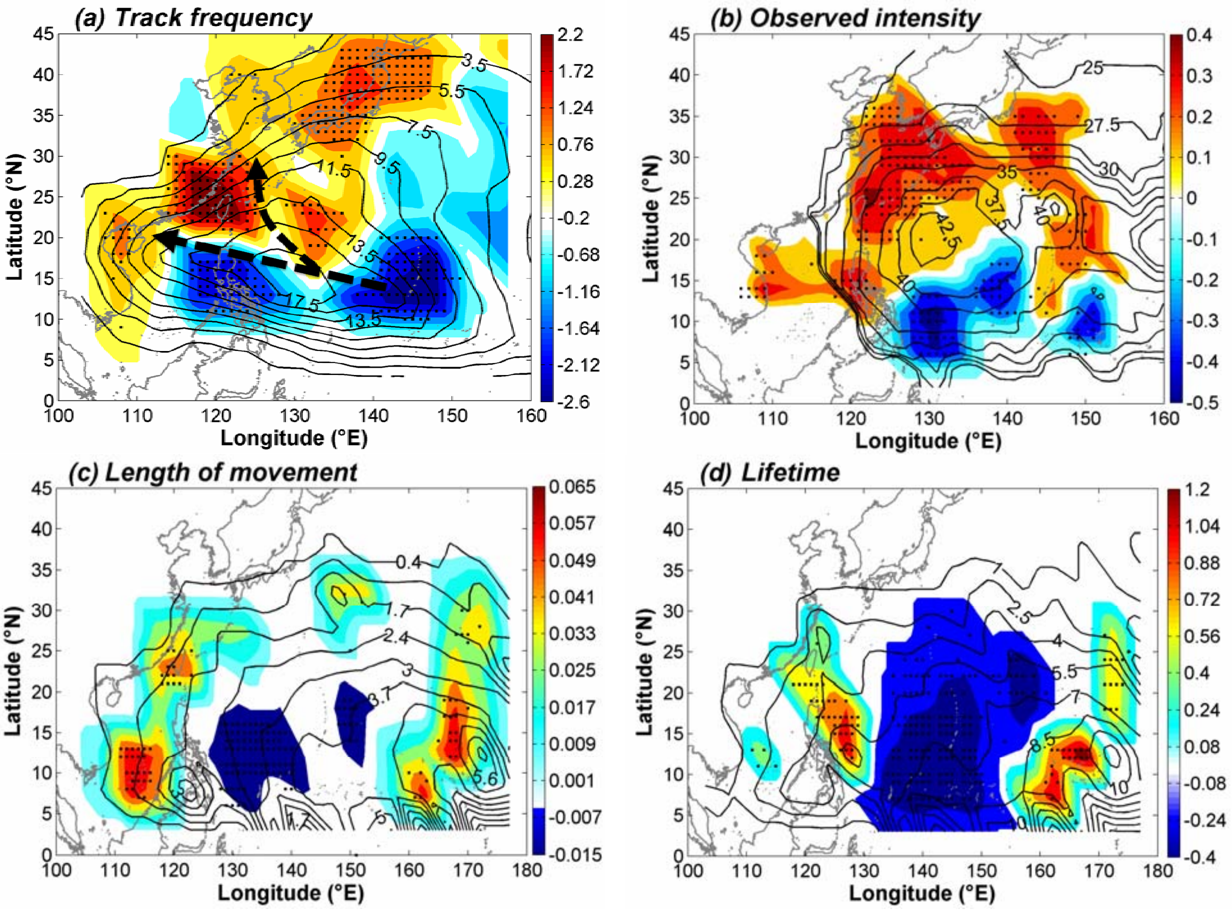

Figure 3. Climatology (contour) and linear trends (shading) over the period 1951–2014 based on the JTWC dataset from (a) track frequency (track frequency: % , trend: % decade^{-1}) and (b) observed intensity (observed intensity: m s^{-1}, trend: m s^{-1} decade^{-1}). Based on the JMA dataset from (c) length of movement (length of movement: 103 km, trend: 103 km decade^{-1}) and (d) lifetime (lifetime: d, trend: d decade^{-1}). Black dots are marked for grid points where the linear trends are statistically significant at the 90% confidence level.

3.3 *Global warming influence on the TC activity*

Regional SST determines the power input, which maintains the formation and development of a TC (Malkus and Riehl[28]; Schade[29]; Saunders and Harris[30]). Simultaneously, it is an important factor that controls TC intensity. Tropical SST has risen by 0.25–0.5°C since the middle of the last century (Houghton et al.[16]; Rayner et al.[31]; Santer et al.[32]). High SST is a necessary but insufficient condition for hurricane intensification (Sun et al.[33]). From the perspective of the global warming scenario, TC intensity is influenced by energy input or upper troposphere thermal exchange (Emanuel[34, 35]; Holland[36]; Henderson-Sellers et al.[37]). From the viewpoint of energy exchange, in the east of the Philippine Sea SST increases, but the TC activity decreases. This is likely due to adverse conditions of heating power and motive power in this region.

Park et al.[38] concluded that the spatial difference of the power environment changes the relative TC intensity patterns. The global warming scenario in recent decades may affect the general circulation of the atmosphere on a large scale, which could result in changes to the vertical wind shear and relative vorticity. To determine the mechanism of the changes to the TC activity, we could examine the changes of the environmental field during TC development. Figure 4a shows the trend in tropical Pacific SST. Over the past seven decades, SST has clearly become warmer over the northwest Pacific, especially over the western Pacific warm pool. In contrast, SST slightly decreases over the middle and east tropical Pacific. This pattern of Pacific SST changes must result in an increasing zonal temperature gradient between the western Pacific and Middle Eastern Pacific. The spatial difference of SST must impact the change in TC activity on a large scale because the coupling process is strengthened near the equator. Such a change would likely result in the strengthening of the Walker circulation. Figure 4b shows that the long-term change in the trend in low attitude circulation along the eastern Pacific near the equator increases, but it decreases westward.

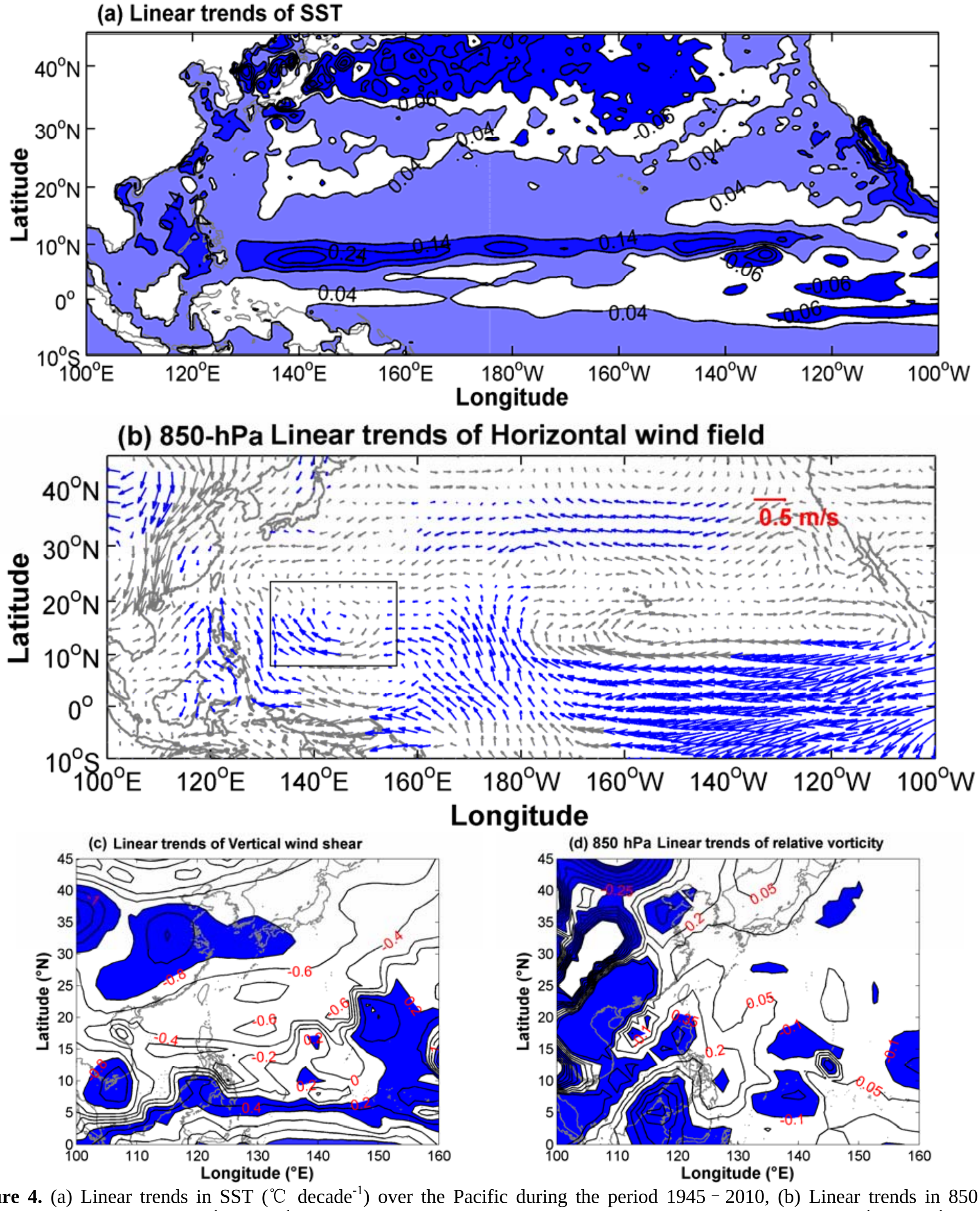

Figure 4. (a) Linear trends in SST (℃ decade^{-1}) over the Pacific during the period 1945－2010, (b) Linear trends in 850 hPa horizontal winds (vectors, m s^{-1} decade^{-1}), (c) the vertical wind shear between 850 and 200 hPa (contours, m s^{-1} decade^{-1}) and (d) relative vorticity (contours, 10-6 m s^{-1} decade^{-1}) over the WNP during the period 1948–2014. Light and dark blue shadings indicate that the trend is statistically significant at the 90% and 95% confidence levels; blue arrows indicate the region by the 90% confidence level.

Related to this enhanced Walker circulation, dynamic environments relevant to TC activity were also examined, such as horizontal winds and relative vorticity at 850 hPa, and magnitude of the vertical wind shear between 200 and 850 hPa (Fig. 4 b, c). The increasing low-level easterlies near the equator form a meridional wind shear, inducing more anticyclonic low-level flows along the tropics, including the eastern region in the rectangle (Fig. 4b). This somewhat anomalous anticyclone may become an important factor for restraining the TC formation. Conversely, the strengthening of the Walker circulation has also increased the magnitude of the vertical wind shear in the tropical North Pacific. The region (137–145°E, 10–15°N) in Fig. 4c and d shows an increasing trend in vertical wind shear and a decreasing trend in relative vorticity. Although changes to the vertical wind shear and relative vorticity are not obvious, they are likely an important factor for lessening TC activity. It may also explain TC genesis frequency and intensity decrease in eastern Philippine. In the subtropical zone of the northern South China Sea, south of Taiwan, and Japan, a large abnormal low level cyclonic wind flows and weakens vertical wind shear. In combination with the warmer SST, this has led to an increase in the strength of TCs. As a result, TCs may reach their maximum intensity more frequently closer to the East Asian continent, i.e., TCs could intensify or sustain their strength up to the brink of landfall. This implies that there might be a significantly increasing trend in landfall intensity of TCs over recent decades along the East Asian coastlines. Changes to the conditions of the ocean and atmosphere over the Northwest Pacific would enhance the threat of TCs along Eastern Asian coastal states.

Therefore, when explaining the observed TC intensity and the spatial distribution patterns of the track density, both thermodynamic and dynamic environments should be considered. However, it appears that dynamic factors are more important than thermodynamic ones.

4 CONCLUSIONS AND DISCUSSION

Utilizing the JTWC and JMA RSMC TOKYO TC best-track data over the period of 1951–2014, the spatial and temporal variability of Northwest Pacific tropical cyclone activity in a global warming scenario has been evaluated. Our conclusions are as follows.

(1) Between the early 1950s and late 1950s, the frequency of TC occurrence rapidly increased, whereas between the early 1960s and 2014, the frequency of TC occurrence decreased. The frequency of occurrence of Northwest Pacific super typhoons decreased between the early 1950s and late 1970s but increased between the late 1970s and 2014. Between 1951 and 2014, the Northwest Pacific TC intensity and peak intensity dramatically decreased. The long-term changes of TC length of movement and lifetime are not very significant, but they exhibit a slightly decreasing trend. From the early 1960s, TC occurrence frequency, intensity, peak intensity, length of movement and lifetime decreased.

(2) From the perspective of the different stages of the life cycle of TCs, the track frequency, observed intensity, length of movement, and lifetime spatial distribution of the observed intensity changes linearly. The regions where the linear changes increase approach the land of eastern Asia. This indicates that Northwest Pacific TC activity decreases, but the frequency of landfalls and intensity are likely strengthened. Therefore, the threat of TCs toward eastern Asia is enhanced.

(3) That is likely because global warming increases the temperature gradient between the northwest Pacific and the central and eastern Pacific, which strengthens the Walker circulation. The strengthened Walker circulation could increase the magnitude of the vertical wind shear and the relative vorticity and the meridional wind shear of low-level easterlies near the equator along the tropical northwest Pacific, which affects the spatial variation of TC activity in the northwest Pacific.

Clearly, global warming may be an important factor that influences northwest Pacific TC activity changes. ENSO cycles and the Pacific Decadal Oscillation (PDO) lead to anomalous atmospheric circulation in the northwest Pacific, which results in the changes of northwest Pacific TC activity (Cane et al.[39]; Zhou et al.[40]; He and Jiang[41]; Zou and Zhao[42]; Tao et al.[43]). Ha and Zhong[44] concluded that the Eastern Indian Ocean–Western Pacific (EIO-WPO) SSTA changes the environmental field barotropic energy to a synoptic scale disturbance by modulating the large scale environmental field.

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